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Kelvin waves in total column ozone

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Abstract. Tropical Kelvin waves have been observed previously in ozone mixing ratio data from the SBUV (Solar Backscatter Ultraviolet) and LIMS (Limb Infrared Monitor of the Stratosphere) instruments on board the Nimbus-7 satellite. The present study investigates Kelvin wave features in total column ozone, using version 6 data from the Total Ozone Mapping Spectrometer (TOMS) instrument (also on Nimbus-7). Results show eastward-propagating zonal waves 1-2 with periods ~5-15 days, amplitudes ~3–5 Dobson Units (1–2 % of the time mean), and latitudinal symmetry typical of Kelvin waves. The analyses and a linear model in this study suggest that the primary source of the perturbations is slow Kelvin waves in the lower-to-middle stratosphere. Maximum Kelvin wave signatures occur in conjunction with westward lower-to-middle stratospheric equatorial zonal winds [a quasi-biennial oscillation (QBO) wind modulation effect]. The significance of these results is that the TOMS data are shown to be useful for investigations with global coverage of a major component of tropical stratospheric dynamics, Kelvin waves. The TOMS data set with its excellent coverage and high quality should be useful in validating model studies in the relatively data sparse and dynamically difficult tropical region.

Introduction

Many observational studies have been done on tropical Kelvin waves, with some of the earliest being Wallace and Kousky [1968], Maruyama [1969], and Angell et al. [1973]. The present investigation examines TOMS total column ozone for signatures of these waves. As will be seen, the lower stratosphere appears to be the primary region responsible for Kelvin waves in total ozone.

Stratospheric Kelvin waves in ozone mixing ratio were studied by Prata [1990] using SBUV data for January 1979. That study reported upper stratospheric Kelvin waves in zonal waves 1 and 2 with periods ~1 week and vertical wavelengths ~15 km. Randel and Gille [1991] examined Kelvin ozone waves in LIMS data for January–February 1979 and SBUV data for January 1979–February 1986. Typical periods of upper stratospheric Kelvin waves were found to vary from 5 to 15 days with vertical wavelengths comparable to those found by Prata. Randel [1990], using LIMS data, showed that there are two primary regions of Kelvin waves in ozone mixing ratio: the upper stratosphere (where photochemistry dominates), and the lower stratosphere (where transport dominates). In the middle stratosphere (~10 hPa), Kelvin wave perturbations in ozone are virtually nonexistent because of vanishing vertical gradients in ozone mixing ratio.

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As noted by Randel and Gille, SBUV vertical resolution is ~8-10 km, and there is also an apparent effect by the processing algorithms that restricts detected vertical wavelengths to 27 km or larger. This makes it difficult to use SBUV data to study Kelvin wave signals in the lower stratosphere (where vertical wavelengths ~6-10 km are common). In contrast, the TOMS data, as will be seen, are sensitive to Kelvin waves in the lower stratosphere.

Three 60-day case studies will be presented below, each exhibiting features typical of tropical Kelvin waves. Two episodes are near solstice, beginning in July, and the third near equinox, beginning in March.

Data and Analysis

This study uses TOMS version 6 daily data from the NASA/Goddard Space Flight Center made available on CD-ROM disk in a format of 1°latitude by 1.25°longitude bins, covering 1 November 1978 to 31 January 1992. These data were regridded in this study onto a 5°× 5°mesh extending from 85°N to 85°S in latitude and 180°to 175°W in longitude. Further details concerning regridded TOMS data and spectral methods are discussed by Stanford and Ziemke [1993].

Tabulated monthly mean zonal winds from Singapore (1°N, 104°E) [B. Naujokat, Free University of Berlin, personal communication] for years 1979-1991 at pressure levels 10–70 hPa were used in this study.

Kelvin Wave Signatures in TOMS

TOMS power spectra for fast (periods < 15 days) zonal waves 1-2 are shown in Figure 1. Three case examples were selected for study here, indicated by E1, E2, and E3; each is 60 days in length and starting dates are 1 July 1981, 15 July 1984, and 1 March 1987, respectively. Monthly mean 30 hPa QBO zonal winds reveal an apparent out-of-phase relationship with the eastward propagating components. A recent study of single-station rawinsonde data by Shiotani and Horinouchi [1993] found a similar relationship, but between westward zonal QBO winds from Singapore and lower stratospheric Kelvin wave activity. The similarity suggests that eastward waves 1-2 spectra in Figure 1 are likely due to lower stratospheric Kelvin waves.

Kelvin wave signatures in total ozone are expected to exhibit eastward propagating waves 1 or 2 with maximum amplitudes along the equator, and periods between 4 and 15 days. The spectra in Figure 2a show eastward waves 1-2 dominating all three episodes along the equator, with periods ~5-15 days. The line of constant phase speed shown in each frame is centered through the zonal wavenumber contributing most to total amplitude. Figure 2b shows structures typical of Kelvin waves, with eastward components exhibiting meridional symmetry and a relative maximum along the equator. All three cases

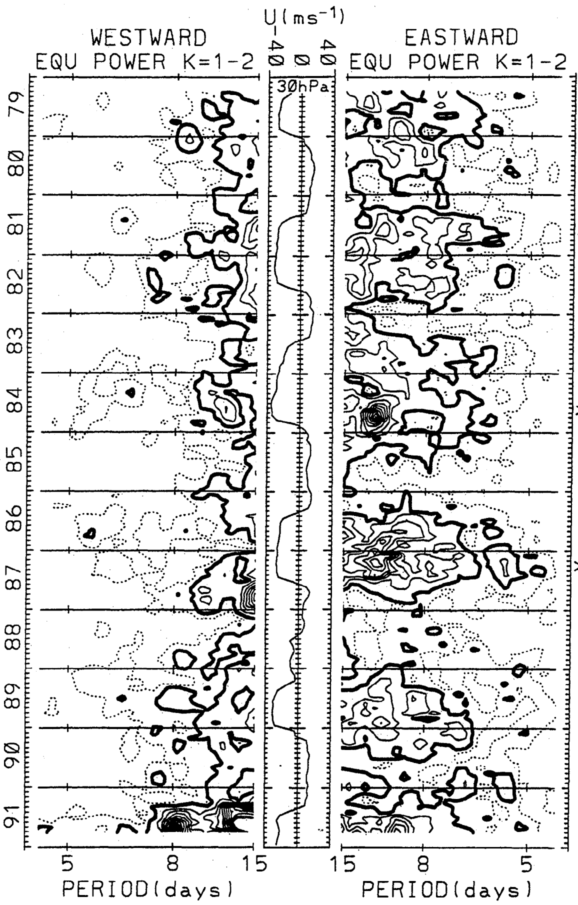

Fig. 1. Calculated westward/eastward TOMS power spectra covering 1979-1991 for combined zonal waves 1-2 along the equator, and 30 hPa monthly mean zonal winds (units ms^{-1}) from Singapore (middle). A 180-day window was stepped forward in time at one-month intervals to compute spectra. Only largest frequencies shown, with periods in days indicated (15, 8, and 5 days). Solid (dashed) contours in spectra are 0.02,0.04,0.06,... (0.01) with 0.02 darkest; units are DU^2-day. Symbols E1-E3 identify three 60-day case studies discussed in text.

could be lower stratospheric "slow" Kelvin waves since phase speeds appear to be less than $\sim$40 ms^{-1} [see, for example, Wallace and Kousky, 1968]. Faster phase speeds (exceeding 60 ms^{-1}) are more generally found in the upper stratosphere [Hirota, 1978; Salby et al., 1984].

Simple zonal wind advection of ozone does not explain these results. Monthly mean zonal winds at Singapore (not shown) for pressure levels 10, 15, 20, 40, 50, and 70 hPa indicate that eastward winds occur only at the lowest and highest altitudes for episodes E1 and E3, respectively, with values less than 12 ms^{-1}. Even at 12 ms^{-1}, the period of eastward propagating zonal wave 1 (2) would be 38 (19) days, which is roughly twice the observed values shown in Figure 2.

Figure 3 shows Hovmöller diagrams for episodes E1-E3. Bandpass filters were applied to retain the primary equatorial spectral responses shown in Figure 2 (no eastward/westward filtering is employed). Oscillation periods are $\sim$6-10 days for each episode when amplitudes appear largest (exceeding 3 DU). Note eastward phase movement of strongest amplitudes, consistent with Kelvin wave dynamics.

Kelvin Wave Modeled Amplitudes in Total Ozone

A model for estimating tropical Kelvin wave amplitudes in total column ozone was formulated using appropriate forms of the linearized thermodynamic [Andrews et al., 1987] and tracer continuity [Salby et al., 1990] equations. The two equations are, respectively,

$$T'_t + \overline{u}T'_x + w'HN^2/R = -T'\tau^{-1} \quad (1)$$

$$\chi'_t + \overline{u}\chi'_x + w'\overline{\chi}_z = -\Gamma\chi' - \theta T' \quad (2)$$

where T is absolute temperature, χ is volume mixing ratio, H=scale height (7 km here), R=gas constant (287 J$\cdot$kg^{-1}K^{-1}), N= buoyancy frequency (taken to be 2×10^{-2} s^{-1}), τ^{-1} is a radiative damping coefficient, Γ and θ are linear photochemical production/destruction parameters (taken to be zero over the vertical range of interest here, z <40 km [Hartmann and Garcia, 1979]), the overbar denotes a zonal average, and subscripts denote partial differentiation. All other symbols are standard. Zonal mean wind $\overline{u}$ is a constant, but remains as a variable parameter (via dispersion relation) in this model.

In (1) we use an approximate empirical form for the radiative damping coefficient given by τ^{-1} (units: s^{-1}) $= A(1 - e^{-B/\lambda_z})\cdot(z/40)^{1.8}$, where $A = 3.7 \times 10^{-6}$ s^{-1}, B=14.8 (km), z is altitude (km), and λ_z =vertical wavelength (km). This expression was constructed upon examining the diagrams of τ^{-1} in Fels [1982, 1984].

Standard interpolated Umkehr profiles (R. McPeters, NASA/GSFC, personal communication) for 250 DU in the tropics were used to estimate $\overline{\chi}_z$ in (2). The bottom of Umkehr level j ($j = 0, 1, 2, ..., 10$) is given by pressure (1013.25)$\cdot 2^{-j}$ hPa; corresponding partial column values ($\Delta\Omega$) for these 11 levels for total column 250 DU are 12, 8.25, 4.5, 11.75, 40, 68.7, 60, 29.4, 10.9, 3.2, and 1.3 DU, respectively. A straightforward vertical weighting by log-pressure density (proportional to $e^{-z/H}$) yields $\overline{\chi} = (\Delta\Omega/H)\cdot 2^{j+1}$ between levels j and $j+1$; associated mean altitude is $H[1 + (j-1)\ln 2]$.

Perturbations in total column ozone Ω' are given by

$$0.772 \times 10^5 \cdot \int_0^\infty dz \cdot \rho \cdot \chi' \approx 10^5 \cdot \int_0^\infty dz \cdot e^{-z/H} \cdot \chi' \quad (3),$$

where units are DU, and ρ, the total mass density, was approximated by $1.3 \cdot e^{-z/H}$ (units: kg-m^{-3}).

For induced Kelvin wave perturbations, the form of χ' is taken to be the real part of $\chi'(x, y, z, t) = \hat{\chi}(y, z) \cdot e^{z/2H} \cdot e^{i(kx+mz-\omega t)}$, where the exponential terms were chosen to balance those of linear Kelvin wave temperature perturbation solutions. Calculation of RMS perturbation amplitudes in total ozone begins by taking $\hat{w}$ (hat symbol $\hat{}$ denotes a spectral amplitude function) from (1), substituting this into (2), thus yielding $\hat{\chi}$. Then χ' (real part) is substituted into (3) which gives Ω'. The real part of χ' is proportional to $\cos(mz + \delta)$, where δ, a function of several phase terms, loops through 200 regularly spaced values from -π to π for the term $kx - \omega t$. Vertical grid spacing for integration is 267 m. Based on Figure 1 of Shiotani and Horinouchi [1993] (corresponding to event E2 in this study), modeled Kelvin wave temperatures were all conservatively taken to be 3°C (half of peak-to-peak) at 4 scale heights for vertical wavelength 10 km (Figure 1 of Shiotani and Horinouchi actually shows $\sim$ 4–5°C); perturbations in total ozone from (3) will be linearly proportional to this value.

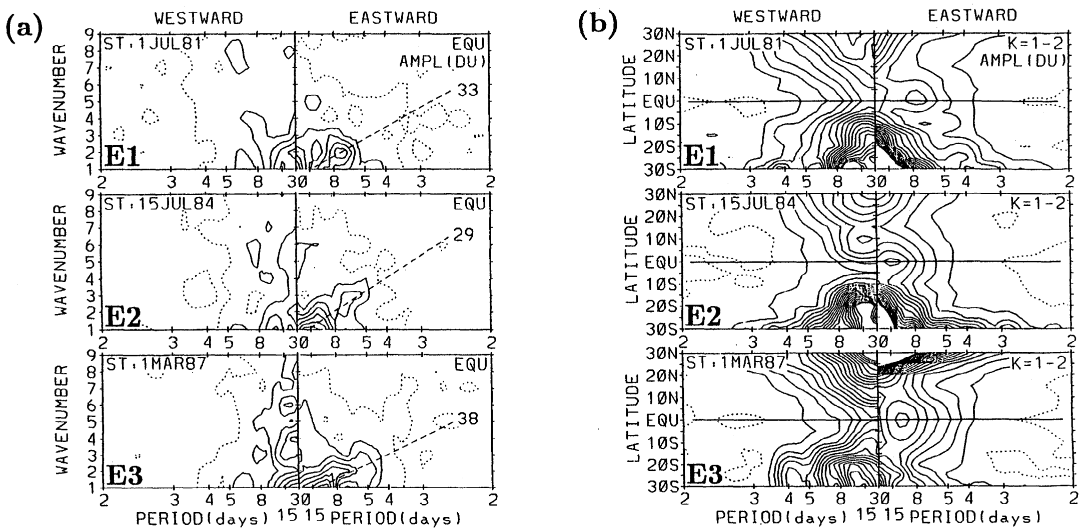

Fig. 2. Spectral amplitudes for episodes E1-E3 with starting dates indicated. All data set lengths are 60 days and all units are DU. Frequency tick marks denote periods 2,3,4,5,8,15, and 30 days. Dashed (solid) contours are 0.1 (0.2,0.3,...). (a) Zonal wavenumber vs. frequency along the equator. Straight dashed line in each frame corresponds to constant eastward phase speed in ms^{-1}. (b) Latitude vs. frequency plots of RMS mean amplitude of combined zonal waves 1-2.

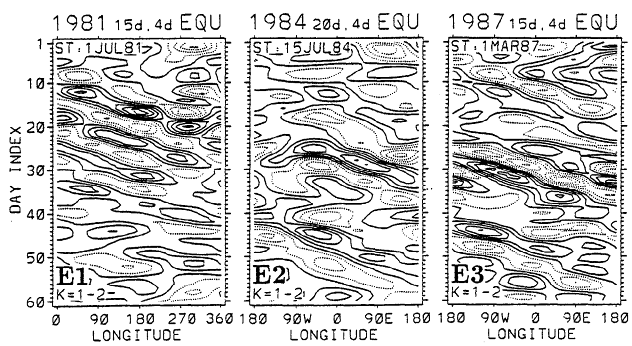

Fig. 3. Time vs. longitude Hovmöller diagrams for case studies E1-E3. Spatial filtering: zonal waves 1-2. E1 and E3 (E2) used a bandpass filter response with half-amplitudes at 15 and 4-day (20 and 4-day) periods. Solid (dashed) contours begin at zero (-1) and increment (decrement) by 1. Units: DU.

Peak perturbation amplitudes in total column ozone are found to be ~1-2 DU for eastward propagating linear Kelvin waves 1 or 2, with vertical wavelengths 5-35 km (Figure 4). Comparing our events E2 and E3 with Figure 3 of Shiotani and Horinouchi, perturbations in ozone for these two events likely come from pressure levels ~15–40 hPa and ~40–70 hPa, respectively. (These two integrations are shown in the figure). Sensitivity in this model depends strongly on $\overline{\chi}_z$ in the lower stratosphere [Salby et al., 1990]; doubling $\overline{\chi}_z$ in this model doubles Ω'.

The significance of this model calculation is that it shows that Kelvin waves should dynamically induce total ozone perturbations of several DU, comparable in magnitude to those observed in TOMS. It is also possible that tropical clouds accompanying Kelvin waves could induce some of the features found here. It should be noted that version 6 TOMS retrievals incorporate algorithms to correct for cloud effects, although their success during the tropical wave episodes E1–E3 is uncertain and it is beyond the scope of this paper to determine the precise role of clouds during these events. However, the model calculations presented above suggest that, even in the absence of clouds, Kelvin waves should dynamically induce ozone signatures comparable in magnitude to those observed in Figure 3.

Summary

1. Tropical Kelvin wave signatures in total column ozone were found in three separate case studies. Observed periods for zonal waves 1-2 were ~5-15 days with amplitudes exceeding 3 DU. While tropical clouds associated with Kelvin waves could contribute to the observed amplitudes, a model calculation (independent of any cloud effects) suggests that lower stratospheric Kelvin wave dynamics alone can induce a significant portion of the observed ozone wave amplitudes.

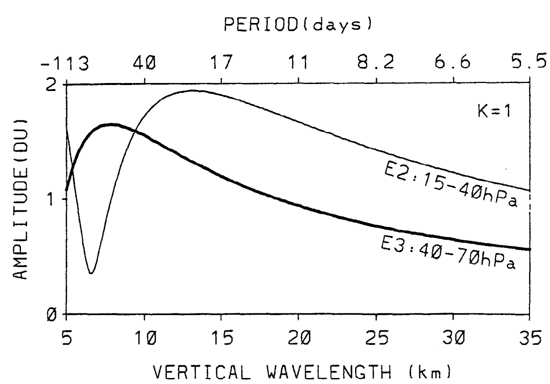

Fig. 4. Peak RMS amplitudes (units DU) of modeled lower stratospheric zonal wave 1 Kelvin wave perturbations in total column ozone plotted vs. vertical wavelength and wave period (obtained from dispersion relation $\omega = k\overline{u} - kN[m^2 + 1/4H^2]^{-1/2}$). Integrations shown roughly correspond to events E2 and E3 (see text). Modeled wave 2 also gives 1–2 DU amplitudes.

2. A distinct tropical QBO synchronization is found between zonal winds and eastward zonal waves 1-2 in total ozone, in contrast to semiannual variations in upper stratospheric Kelvin ozone waves found by earlier investigators. This is consistent with eastward Kelvin waves in TOMS data being influenced more by QBO-modulated Kelvin waves in the lower-to-middle stratosphere than at higher altitudes. Further comparison with a previous study using tropical rawinsonde data indicates that the episodes investigated in this study are caused by Kelvin waves in the lower stratosphere around 20–70 hPa.

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References

Andrews, D. G., J. R. Holton, and C. B. Leovy, Middle Atmosphere Dynamics, Academic Press, Inc., New York. pp. 489, 1987.

Angell, J. K., G. F. Cotton, and J. Korshover, A climatological analysis of oscillations of Kelvin wave period at 50 mb. J. Atmos. Sci., 30, 13–24, 1973.

Fels, S. B., A parameterization of scale-dependent radiative damping rates in the middle atmosphere. J. Atmos. Sci., 39, 1141–1152, 1982.

Fels, S. B., The radiative damping of short vertical scale waves in the mesosphere. J. Atmos. Sci., 41, 1755–1764, 1984.

Hartmann, D. L., and R. L. Garcia, A mechanistic model of ozone transport by planetary waves in the stratosphere. J. Atmos. Sci., 36, 350–364, 1979.

Hirota, I., Equatorial waves in the upper stratosphere and mesosphere in relation to the semiannual oscillation of the zonal wind. J. Atmos. Sci., 35, 714–722, 1978.

Maruyama, T., Long-term behavior of Kelvin waves and mixed Rossby-gravity waves. J. Meteor. Soc. Japan, 47, 245–254, 1969.

Prata, A. J., Travelling waves in Nimbus-7 SBUV ozone measurements: Observations and theory. Q. J. R. Meteor. Soc., 116, 1091–1122, 1990.

Randel, W. J., Kelvin wave-induced trace constituent oscillations in the equatorial stratosphere. J. Geophys. Res., 95, 18641–18652, 1990.

Randel, W. J., and J. C. Gille, Kelvin wave variability in the upper stratosphere observed in SBUV ozone data. J. Atmos. Sci., 48, 2336–2349, 1991.

Stanford, J. L., and J. R. Ziemke, Rossby-gravity waves in tropical total ozone. Geophys. Res. Lett., 20, 2239–2242, 1993.

Salby, M. L., P. Callaghan, S. Solomon, and R. R. Garcia, Chemical fluctuations associated with vertically propagating equatorial Kelvin waves. J. Geophys. Res., 95, 20491–20505, 1990.

Salby, M. L., D. L. Hartmann, P. L. Bailey, and J. C. Gille, Evidence for equatorial Kelvin modes in Nimbus-7 LIMS. J. Atmos. Sci., 41, 220–235, 1984.

Shiotani, M., and T. Horinouchi, Kelvin wave activity and the quasi-biennial oscillation in the equatorial lower stratosphere. J. Meteor. Soc. Japan, 71, 175–181, 1993.

Wallace, J., and V. Kousky, Observational evidence of Kelvin waves in the tropical stratosphere. J. Atmos. Sci., 25, 900–907, 1968.

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